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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER M50/86	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Exercise endurance time as a function of percent maximal power production		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Everett A. Harman, Howard G. Knuttgen, Peter N. Frykman and John F. Patton		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS JS Army Research Institute of Environmental Medicine Natick, MA 01760-5007		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Same as 9. above.		12. REPORT DATE July 1986
		13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution is unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) cycle ergometer; endurance time; curve fitting		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) To develop and statistically validate a mathematical model of the relationship between power production and endurance time (T), 15 male subjects were first tested for maximal power on an instrumented cycle ergometer at 60 RPM. On subsequent days they were tested for T at various percentages of maximal power. Curves of T as a function of percent maximal power were curvilinear, and could be made to overlap among subjects by individual abscissa scaling, which resulted in the appearance of horizontal stretching or compression of the curves. The degree of stretching-compression was defined by a statistically obtained scaling		

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factor (F) which served to quantify each subject's endurance ability at fractions of maximal power. F was used to transform percent of maximal power to a scaled power variable (P_{sc}). A curve of the form $T=a(P_{sc})^b$ was developed on 10 of the subjects and validated on the remaining five. Correlation between predicted and actual T was 0.967 for the fitting group and 0.980 for the validation group. A maximal power test and a single endurance test at 40-50% of maximal power were found to establish individual endurance-power curves fairly well, with a correlation of 0.828 between actual and predicted T. The combination of F and maximal power for a given physical activity provide a profile of an individual's ability to perform.

SCIENTIFIC PAPER

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Exercise endurance time as a function of percent maximal power production

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Running head:

Endurance time as a function of percent maximal power

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Exercise endurance time as a function of percent maximal power production

ABSTRACT

To develop and statistically validate a mathematical model of the relationship between endurance time (T) and power production, 15 male subjects were first tested for maximal power on an instrumented cycle ergometer at 60 RPM. On subsequent days they were tested for T at various percentages of maximal power. Curves of T as a function of percent maximal power were curvilinear, and could be made to overlap among subjects by individual abscissa scaling, which resulted in the appearance of horizontal stretching or compression of the curves. The degree of stretching-compression was defined by a statistically obtained scaling factor (F) which served to quantify each subject's endurance ability at fractions of maximal power. F was used to transform percent of maximal power to a scaled power variable (P_{sc}). A curve of the form $T=a(P_{sc})^b$ was developed on 10 of the subjects and validated on the remaining five. Correlation between predicted and actual T was 0.967 for the fitting group and 0.980 for the validation group. A maximal power test and a single endurance test at 40-50% of maximal power were found to establish individual endurance-power curves fairly well, with a correlation of 0.828 between actual and predicted T. The combination of F and maximal power for a given physical activity provide a useful profile of an individual's ability to perform at constant exercise intensity. —

cycle ergometer; endurance time; curve fitting

INTRODUCTION

The fastest means of supplying energy in exercising muscle is the breakdown of intracellular high energy phosphate stores, which can occur at high rates for only a few seconds. Anaerobic glycolysis can provide ATP for a longer period of time, but at a lower maximum rate. The slowest process for ATP resynthesis is oxidative phosphorylation, which can operate for the longest period. Exercise at a given power level is fueled mainly by the slowest of the systems that can produce energy at the required rate, allowing the exercise to be carried out for as long as possible. High, medium, and low intensity exercise may be respectively defined as physical activity primarily fueled by breakdown of intracellular high energy phosphates, anaerobic glycolysis, and oxidative phosphorylation.

Investigations performed on both sustained isometric (6,8) and dynamic exercise (1,2,5,7,8,9,10) have demonstrated a generally curvilinear relationship between endurance time and exercise intensity. Throughout the upper range of power production, fueled primarily via the anaerobic systems, sizable decreases in energy demand result in only small increases in endurance time. As exercise becomes less intense, and the muscles are able to turn increasingly to aerobic metabolism for energy production, decreases in exercise intensity result in larger and larger increases in endurance time. As energy demand is decreased to levels which can be supported almost entirely by aerobic metabolism, endurance time increases very greatly with even modest decreases in power production. A point is reached where only a slight decrease in exercise intensity results in manifold increase in endurance time.

It must be noted that in this article, "maximal" power refers to the highest power a subject can generate for one second, and not to the exercise intensity eliciting $\dot{V}O_{2\text{ max}}$, which is usually less than one-third of the maximal power referred to above. By the same token, "submaximal" refers to the range of intensities below maximal power, a segment of which is higher than the intensity at which $\dot{V}O_{2\text{ max}}$ occurs.

Equations have been derived by various investigators to describe the relationship between endurance time and exercise intensity. For isometric exercise, endurance time has been specified as a function of either absolute force or force expressed as a percentage of the individual's maximum (6,8). For dynamic exercise, endurance time was taken as a function of absolute power (2,5,7,8,9,10). Another approach involved prediction of endurance time from exercise intensity and $\dot{V}O_{2\text{ max}}$ (1). In none of these studies were correlations or other statistical evaluations reported for equation-predicted vs. actual endurance times. However, Wilkie (10), reported problems in the fit of his and similar equations (2,5) to data from trials lasting approximately 10 minutes or of very brief duration.

The purpose of this study was to use curve fitting procedures to develop and statistically evaluate a model describing the relationship between endurance time and percent maximal power during large muscle dynamic exercise, ranging in intensity from levels low enough for aerobic metabolism to provide most of the required energy up to maximal power. The model was to describe the actual relationship between endurance time and power and not be a predictive equation incorporating physiological variables. Due to differences in body dimensions, age, genetic endowment, and physical activity levels, it was anticipated that the relationship of

endurance to power production would differ among individuals. Therefore, the mathematical formulation describing the endurance-power relationship was designed to quantify individual differences in submaximal endurance capability. Such quantification could later be statistically related to such physiological parameters as muscle mass, muscle fiber-type distribution, and the degree of development of systems for both anaerobic and aerobic energy release. An acceptable model would allow reasonably accurate prediction of endurance time for a given subject exercising at a particular power level.

METHODOLOGY

The experiment was conducted in accordance with the policy statement of the American College of Sports Medicine (MEDICINE AND SCIENCE IN SPORTS 10:ix-x,1978) and U.S. Army regulations AR 70-25 and USAMRDC 70-25 on use of volunteers in research, which require that human subjects give free and informed voluntary consent before participation.

Cycle ergometer data collection and processing system

The cycle ergometer used for testing has been described by Knuttgen et al. (3). It can be set at a wide range of resistive intensities up to and including an individual's maximal power, which for most subjects is beyond the power limitations of standard cycle ergometers. The subject can be seated either above the pedals on a normal bicycle saddle or behind the crank in a rigid metal armchair. The rigid chair was used in this study since the high forces during maximal power pedalling tend to make a subject

rise off a standard bicycle saddle. The distance from chair to pedal crank was set for each subject so that the knee never quite reached full extension during cycling.

The cycle ergometer was fitted with strain gage instrumented pedals to accurately measure the pedalling forces exerted by a subject. The angle of each pedal relative to its crank-arm and the angular position of the crank itself were reflected in the voltages output by rotary potentiometers. After they were amplified and conditioned, the transducer signals were digitized by A/D converters and sampled at 100 Hz per channel by a PDP 11/40 computer. Files containing columns of numbers corresponding to transducer output were transferred to a VAX 780 computer where conversion was made to meaningful units of force and angle.

A FORTRAN program used the pedal angle information to calculate the component of pedalling forces tangential to the pedalling arc. Only force exerted in the tangential direction acts to turn the pedals. The metabolic energy used to generate other components of force is dissipated as heat and results in no cycling power.

Work done by the feet on the pedals during a sample interval was calculated as follows:

$$W = A \cdot R (F_{TL} + F_{TR}) \quad (1)$$

where

W = work (J)

A = angle of crank travel (radians)

R = distance from crank pivot to pedal (m)

F_{TL} = tangential force exerted by the left foot (N)

F_{TR} = tangential force exerted by the right foot (N)

Mean power was calculated by summing the work done during the sample intervals within a time span and dividing by the total number of seconds in the span.

Experimental procedure

Subjects were 15 males, most of whom engaged in some form of regular physical exercise, whose height, weight and age were respectively 1.81 ± 0.05 m, 80.8 ± 11.2 kg and 28.3 ± 9.3 yrs. On the first data collection day, each subject was tested for maximal one-revolution power generated on the cycle ergometer at 60 RPM.

Each maximal power test was preceded by a brief period of subject warmup. The cycle was then set at 60 RPM, at which the subject pedalled freely. After a countdown, the experimenter pushed a button to initiate computer sampling and the subject began pedalling with maximal effort. Sampling started as the left crank-arm passed the forward horizontal and continued for five full revolutions. A computer program calculated the mean power for each full revolution as described above. Maximal power was taken as the highest mean power generated during a single revolution.

Each subject was tested for maximal power four times, with a minimum 20-minute rest between tests. An individual's maximal power was taken as the mean of the middlemost two test scores, to avoid the influence of an aberrant test result. On following days, subjects were tested for their endurance times at various fractions of maximal power to establish an endurance-power curve for each individual. A maximum of two endurance trials were run on a subject each test day, and ample recovery time was

allowed between trials to minimize the effects of fatigue. Two trials requiring exercise in excess of five minutes were never performed on the same day.

Before performing an endurance trial, a subject first warmed up by pedalling for five minutes on the cycle ergometer set in constant speed mode at 60 RPM and then rested for three to five minutes. Cycle resistance was then set according to the percentage of maximal power at which the subject was to exercise. The cycle was again run at 60 RPM and the subject pedalled freely without trying to push against the pedals, allowing the cycle's electric motor to carry his legs. The experimenter orally signalled the subject when to begin pedalling, at the same time starting electronic timers and flipping a switch on the control panel which caused the motor to attempt to slow cycling speed by 10%. The subject had to generate power at a level set by the investigator on the control box to maintain ergometer speed at 60 RPM. An analog panel meter in front of the subject indicated whether speed was being maintained. A metronome set at 120 beats per minute gave the subject additional assistance in maintaining pedalling cadence. Experimenters observed a digital speed display and gave warning when RPM's dropped. When a subject began to have extreme difficulty maintaining pedalling speed, he was verbally encouraged to continue. The test was ended when the subject dropped more than three percent below the set speed for seven seconds. The seven seconds were then subtracted from the total time of exercise.

All subjects were tested for endurance time at 36, 45, 54, 63, 72, and 81 percent of maximal power. In addition, subjects who could not endure more than five minutes at 36% were tested at lower relative intensities in

order to provide sufficient information to establish each individual's endurance time vs. percent maximal power curve. Extra trials were performed to provide additional curve points in the region where small decreases in power production resulted in large increases in endurance time. Subjects had a mean of nine trials.

Since the study was focused on the intensity range between maximal power and the level at which energy begins to be largely provided aerobically, an attempt was made to select each subject's lowest exercise intensity as that at which he could endure no longer than about 10 minutes. However, because some individuals showed exceptional relative endurance, and because at low intensity levels small changes in power production bring about very great changes in endurance time, some subjects were able to endure considerably longer than 10 minutes at their lowest power setting. Such data points were included in the curve fitting.

To perform the curve fitting, a FORTRAN program was written which employed the methodology of Kolb (4). It produces coefficients for a number of different equations to best fit a set of data and provides statistical evaluation of the adequacy of fit of each equation. The fitting procedure was performed on the data of 10 of the subjects chosen at random and tested for validity on the data of the remaining five subjects.

RESULTS

When endurance times were plotted against power production, a curvilinear relationship was observed similar to those reported for other types of exercise (1,2,5,6,7,8,9,10). Figure 1a represents group data from

the 10 subjects in the fitting group for endurance time vs. power in watts. Figure 1b compares 3 selected individuals, of whom subject 1 had both the highest maximal power and the shortest endurance times at intensities below 350 watts. Subject 2 had higher maximal power than did subject 3, but their endurance times were very similar at intensities below 400 watts.

Figure 2a illustrates endurance time of the subjects as a function of exercise intensity expressed as percentage of each individual's maximal power. Normalizing for percent maximum provided a common endpoint for all subjects' curves at 100%. Yet the increased point scatter of figure 2a relative to figure 1a indicates that percent maximal power was actually a poorer predictor of endurance time than was absolute power. Percent maximal power curves of the three selected individuals (Figure 2b) were even more divergent than were their absolute power curves, indicating considerable inter-subject difference in endurance time at fractions of maximal power.

Curves for different individuals, though not congruent, were similar in shape, leading to the hypothesis that if a different abscissa scale were used for each subject, the curves could be made to overlap. An individual's scaling could then be used to characterize his relative power and endurance.

A convenient method of employing a separate abscissa scale for each subject was to have a common abscissa called "scaled power", with each subject given a scaling factor which would transform the intensities at which he exercised to scaled power units so that endurance time vs. scaled power curves for different individuals would coincide.

In the graphs of endurance time vs. percent maximal power, curves for different individuals coincided by definition at 100% of one-second maximal

power, although they diverged at power production levels below 100%. To make the curves coincide over their full range required a horizontal stretching or shrinking of the curves away from or towards 100% maximal power. The process used a different scaling factor for each subject as follows:

$$P_{sc} = 100 - F(100 - P_{pmax}) \quad (2)$$

where

P_{sc} = scaled power

F = the individual's scaling factor

P_{pmax} = power expressed as percent of the individuals maximum

It can be seen that when P_{pmax} equals 100 or if the scaling factor is 1.00, P_{sc} equals P_{pmax} . When P_{pmax} is less than 100, if F is greater than 1.00, P_{sc} is less than P_{pmax} , and if F is less than 1.00, P_{sc} is greater than P_{pmax} . Thus, a scaling factor above 1.00 stretches an individual's endurance time vs. scaled power curve to the left, while a scaling factor below 1.00 compresses the curve to the right.

In order to determine scaling factors for each individual, an interactive computer graphics program was written in FORTRAN. It allowed visual stretching of the curves to make them coincide, and created a file with scaling factors for each individual depending on how much the experimenter decided to visually stretch or shrink each curve horizontally. To stretch or shrink a curve, the terminal screen cursor was placed on any point on a subject's curve and a key pressed. The cursor was then moved horizontally left or right to where the experimenter wanted the point to

lie on the scaled power curve. The program calculated the scaling factor F to be used in equation 2 to move the point to the desired location as follows:

$$F = (100 - x_{\text{new}})/(100 - x_{\text{old}}) \quad (3)$$

where

x_{new} = new x coordinate of point

x_{old} = old x coordinate of point

After the old and new locations were indicated with the cursor, the program calculated an F factor as above, used F to modify the abscissae of all of that subject's points using equation 2, and plotted the new curve on the screen. The program operator adjusted the F factor as many times as desired until the resulting curve of endurance time vs. scaled power was stretched or compressed horizontally to the desired degree.

The first step in developing endurance time vs. scaled power curves that overlapped closely among individuals was to stretch or compress all subjects' curves to coincide on the graphics display. This was done by arbitrarily choosing one subject and stretching or compressing the curves of all of the other subjects to coincide as closely as possible to his. As the interactive process was performed, the program created a computer file containing the scaling factor for each subject. The F value for the unmanipulated curve was 1.00.

It was deemed desirable to have the single scaled power curve resulting from the stretching or compression of all of the subjects' percent maximal power curves coincide with the average subject's percent maximal power

curve, so that scaled power would indicate at what percentage of maximal power the average subject could be expected to endure a given amount of time. Thus, the individual scaling factors resulting from the first visual curve stretching procedure were each multiplied by a constant that would make the mean of all the subjects' factors equal 1.00. Thus, any subject having a factor above 1.00 would be better than average in submaximal endurance in the sense that he could tolerate exercise for a given amount of time at a higher percentage of maximal power than could the average subject. By the same token, a subject having a factor less than 1.00 would have to exercise at a lower percentage of maximal power than would the average subject to endure for a given amount of time. Such a subject could thus be characterized as having relatively low submaximal endurance.

Using the endurance time vs. scaled power points as input, the curve fitting computer program produced a best-fit equation of the form:

$$T = a(P_{sc})^b \quad (4)$$

where

T = endurance time (min)

a and b = constants selected by the fitting program

P_{sc} = scaled power (% max)

Since the visual curve stretching had been subjective, an objective method was developed to adjust the subjects' scaling factors so that the data points would come as close to the fitted curve as possible. Scaled power corresponding to the endurance time from each of a subject's trials

was calculated using an equation derived by solving equation 4 for P_{sc} :

$$P_{sc} = (T/a)^{1/b} \quad (5)$$

Thus, each subject had a paired set of P_{pmax} and P_{sc} values corresponding to the percent max power at which the individual endured for the trial, and the percent of maximal power at which the average subject would have endured for the same amount of time. From these, difference-scores from 100 were obtained:

$$D_{pmax} = 100 - P_{pmax} \quad (6a)$$

$$D_{sc} = 100 - P_{sc} \quad (6b)$$

Considering all the pairs of D scores for an individual, there was one value of F that would best fit the equation

$$D_{sc} = F \cdot D_{pmax} \quad (7)$$

Using the pairs of D_{sc} and D_{pmax} values for each subject, a zero intercept linear regression computer program determined the F that best fit each individual's data. Using the objectively determined F's, each individual's scaled power abscissae were recalculated. The curve fitting program was run on the new set of endurance time vs. scaled power points for all 10 subjects in the fitting group. The process yielded a final set

of constants for equation 4. They were:

$$a = 3.706 \times 10^7$$

$$b = -4.444$$

For the 10 subjects in the fitting group, correlation between actual endurance time and that calculated from scaled power using equation 4 was 0.967. Figure 3 shows endurance time vs. scaled power for the 10 subjects in the fitting group, and a plot of equation 4.

The validity of equation 4 for prediction of endurance times of individuals outside the fitting group was tested on the five subjects whose data were not used in the fitting procedure. Each subject's scaling factor was determined from the regression procedure based on equation 7. For the five subjects, correlation between actual and predicted endurance times was 0.980. The high correlation supports the validity of equation 4 for prediction of an individual's endurance time at a given power level if both his maximal power and scaling factor are known. Descriptive statistics for both maximal one revolution cycling power and individual scaling factor, based on the data of all 15 subjects, are presented in Table 1.

The predictive value of equation 4 depends on accurate determination of F for each individual. It was demonstrated above that when F is determined from regression based on the results of 8 or more endurance trials, predicted endurance times correlate highly with the actual times. However, it is desirable to characterize an individual's muscular endurance at percentage of maximal power with a minimum number of tests. For any number of trials greater than one, the regression procedure previously described

can be used to estimate an individual's F factor. If only a single endurance test is performed regression cannot be used, and F is estimated by first employing equation 5 to calculate the P_{sc} corresponding to the trial endurance time, and solving for F as follows:

$$F = (100 - P_{sc}) / (100 - P_{pmax}) \quad (8)$$

To determine how accurately single endurance trials predict F , and to compare the predictive value of single tests at different percentages of maximal power, estimations were made of F for each individual, using the results of each of his endurance trials. An index of the adequacy of a single trial scaling factor estimation was obtained by dividing the F estimated from a single test by the F calculated by regression on all of the individual's tests. An index of 1.00 would mean excellent single test estimation of F .

Each test of all 15 subjects was used to estimate individual F 's, and an adequacy index was computed for each estimate. Table 2 shows descriptive statistics on the adequacy index, grouped according to the percentage of maximal power of the predictor test. A mean index of 1.00 and a standard deviation of 0.00 for a test grouping would indicate that each test in the category perfectly estimated the individual's F obtained from regression on all his tests. It is apparent that mean adequacy indices closest to 1.00 were obtained on tests performed below 50% of maximal power, where small standard deviations support the likelihood of good estimation of an individual's F from a single test.

To have a valid endurance time at a submaximal power level, a subject must not be able to cycle indefinitely. Also, it is not time-economical to use a very long test to characterize a subject's endurance. Some subjects could cycle in excess of 40 minutes at power levels below 40% of maximum. The 40-50% of maximal power test grouping was the lowest category in which none of the subjects could pedal more than 30 minutes. To test the suitability of 40-50% maximal power tests for single test estimation of F, a program was written which calculated each subject's F and all of his endurance times from each single trial within the category. Correlation between F values determined from regression on the results of all the tests of each subject and the F's predicted from single tests at 40-50% of maximal power was 0.951. Correlation between actual endurance time and that predicted by single 40-50% maximal power tests was 0.828.

DISCUSSION

The mathematical formulation developed in this study has been found to adequately describe the relationship of endurance time to power generation for leg ergometer exercise at 60 RPM. Curves of endurance time vs. power production for different individuals were shown to be similar in shape, and could be made to overlap through manipulation of abscissa scaling. The F scaling factor serves as a good quantitative descriptor of individual endurance during submaximal power production. The combination of F and maximal power provide a profile of an individual's ability to perform constant intensity exercise.

The most accurate F for an individual is obtained from regression on a number of endurance trials. However, a fair estimate of F can be obtained from a single endurance trial in the range of 40-50% of maximal power. Forty-five percent of maximal power would constitute a desirable exercise intensity to use for a single predictor test, since no subject tested was able to pedal indefinitely at that level. A large majority of the subjects could not cycle more than five minutes at 45% and the only subject able to endure longer than 20 minutes was a highly trained endurance athlete regionally competitive in the triathlon.

The equation expressing endurance time as a function of resistance can be used to predict how long an individual can be expected to endure at a given percentage of maximal power. To estimate endurance time for an average individual, an F of 1.00 can be assumed. More individualized prediction necessitates calculation of a subject's F from one or more endurance trials.

In the absence of direct assessment, it can be safely assumed that individuals in a randomly selected subject group vary greatly in maximal oxygen uptake, muscle mass, aerobic and anaerobic enzyme activity in the muscle cells, and related physiological parameters. It is not surprising then, that subjects in the present study differed greatly in endurance performance at a variety of absolute power production levels. The differences in endurance time were even greater when power production was expressed relative to each individual's maximal power. Yet endurance results of different individuals became impressively similar when the curve stretching/compression technique was employed. The major physiological conclusion is that, while the capacities of the various energy-yielding

processes differ greatly among individuals, patterns of interaction and overlapping among these processes are remarkably similar.

The endurance time vs. power production equation derived in this study can be assumed to apply only to pedalling activity at 60 RPM. Pedalling at another rate might require a different equation, as might continuous exercise other than cycling. It would be highly desirable to test endurance time vs. power production using both cycling exercise at speeds other than 60 RPM and continuous activities other than cycling. Information would be provided as to how the cadence of a cyclic exercise and the accompanying changes in muscle shortening velocity affect endurance time, and to what degree the relationship of endurance to power generation remains constant across different physical activities. It seems reasonable to hypothesize that the same basic exponential equation, with constants different than those found for 60 RPM cycling, would fit endurance time vs. power production data for a wide range of activities.

The curve-fitting methodology of this study could be used to derive equations specific to other activities. Requisite for such experimentation would be an ergometric device allowing speed to be set and power to be measured, such as commercially available isokinetic dynamometers. A visual or auditory feedback system would have to be implemented to keep the subject at the specified level of power generation. A treadmill could be used, but accurate power calculation would be difficult. Also, procedures would have to be developed to ensure subject safety at the point of failure to maintain running speed.

An individual's F factor, which describes endurance during submaximal power production should be similar for different exercises involving the

same muscle group and repetition rate. The relative endurance of a subject's muscle can be expected to remain relatively constant over different activities.

The F factor by itself does not describe endurance ability at a particular absolute level of power. The subject's maximal power must be known in order to convert the absolute load to percent of the individual's maximum before endurance time can be predicted. A high F value indicates good endurance at fractions of maximal power. However, an individual with a high F but low maximal power may actually have a shorter endurance time at a particular absolute power level than another person with a lower F but high maximal power, since for the latter individual, the power level may be a considerably lower percentage of maximum.

Because maximal power and the F factor together provide a good description of an individual's ability to sustain power generation over a wide range of intensities, a logical follow-up to the present study would be to measure a number of physiological and biochemical variables to determine their relationship to maximal power and the F factor.

ACKNOWLEDGEMENTS

The authors would like to give special thanks to the test subjects who repeatedly endured considerable discomfort while exercising to failure.

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision.

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LEGENDS FOR FIGURES

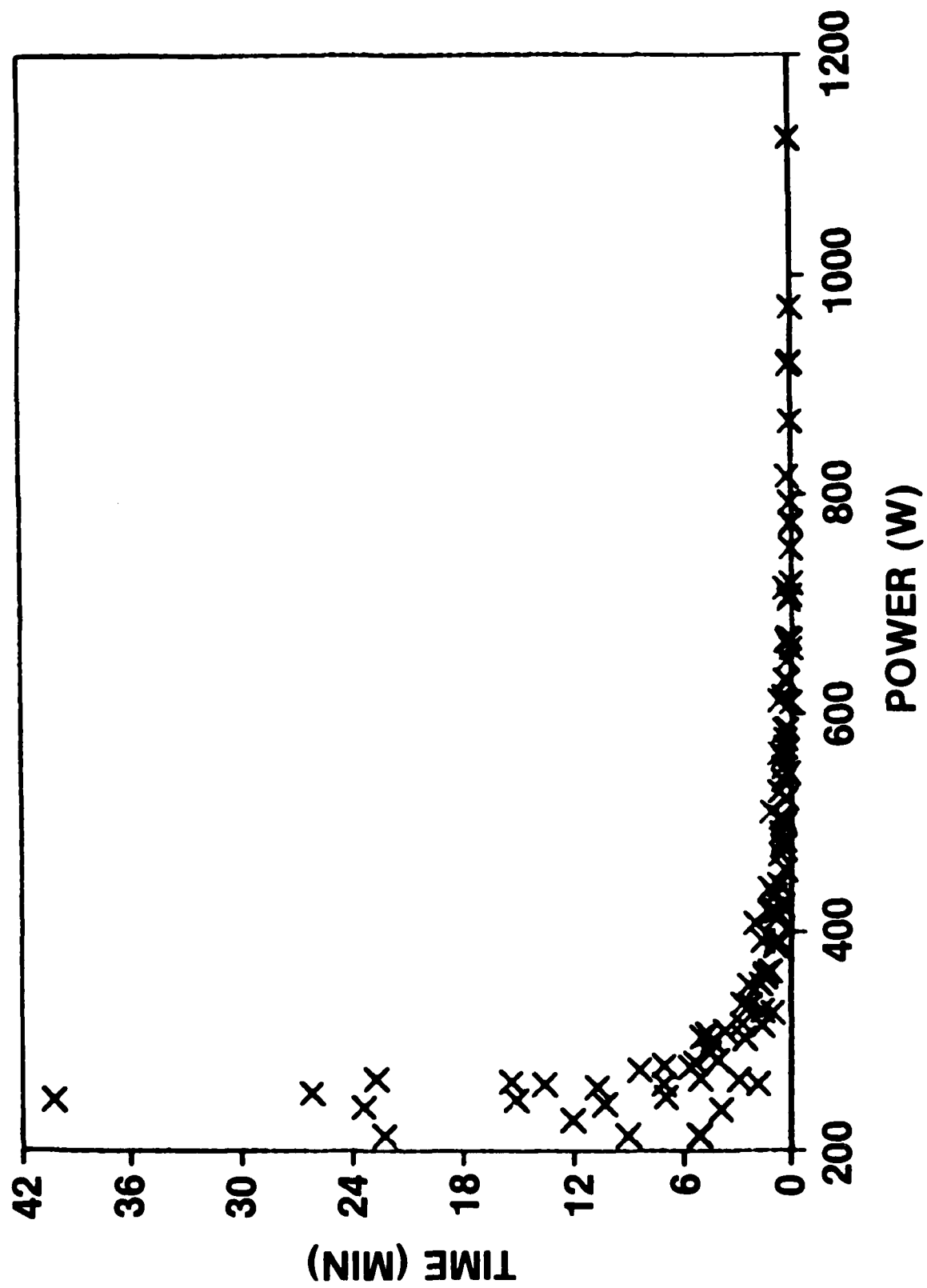
Figure 1. Endurance time (min) vs. power production (W)

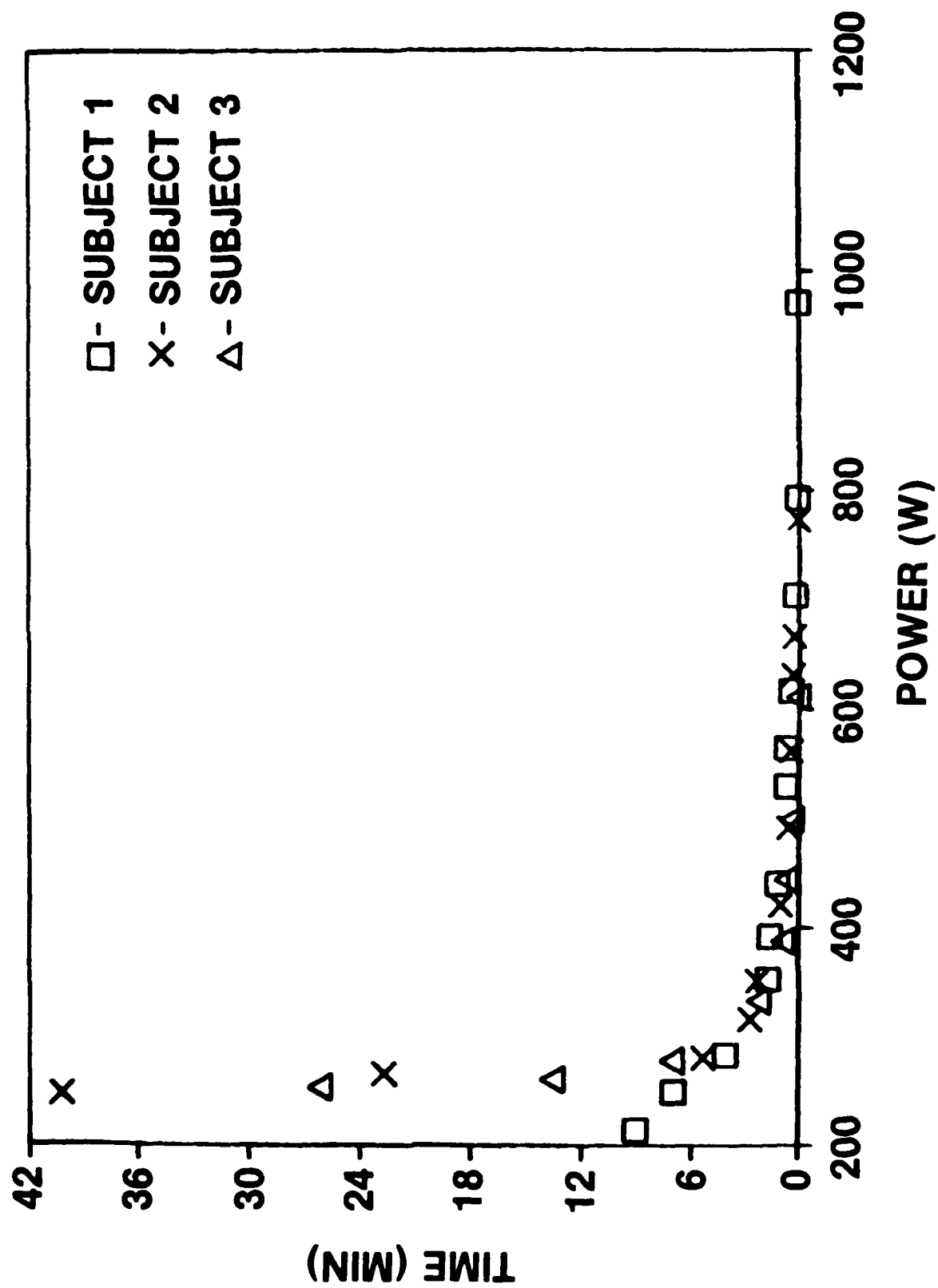
for: a) the fitting group, and b) three different individuals

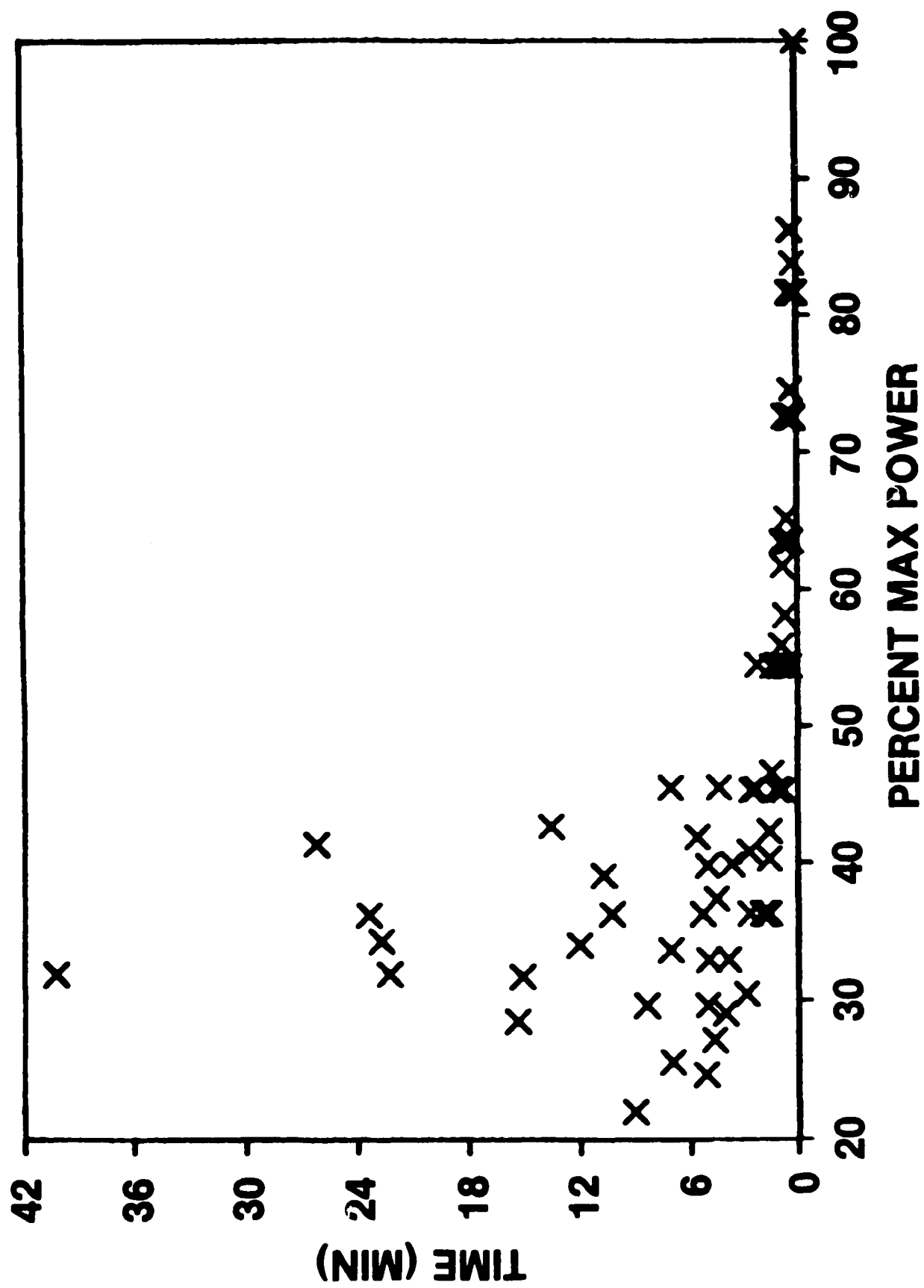
Figure 2. Endurance time (min) vs. power production (% of maximal power)

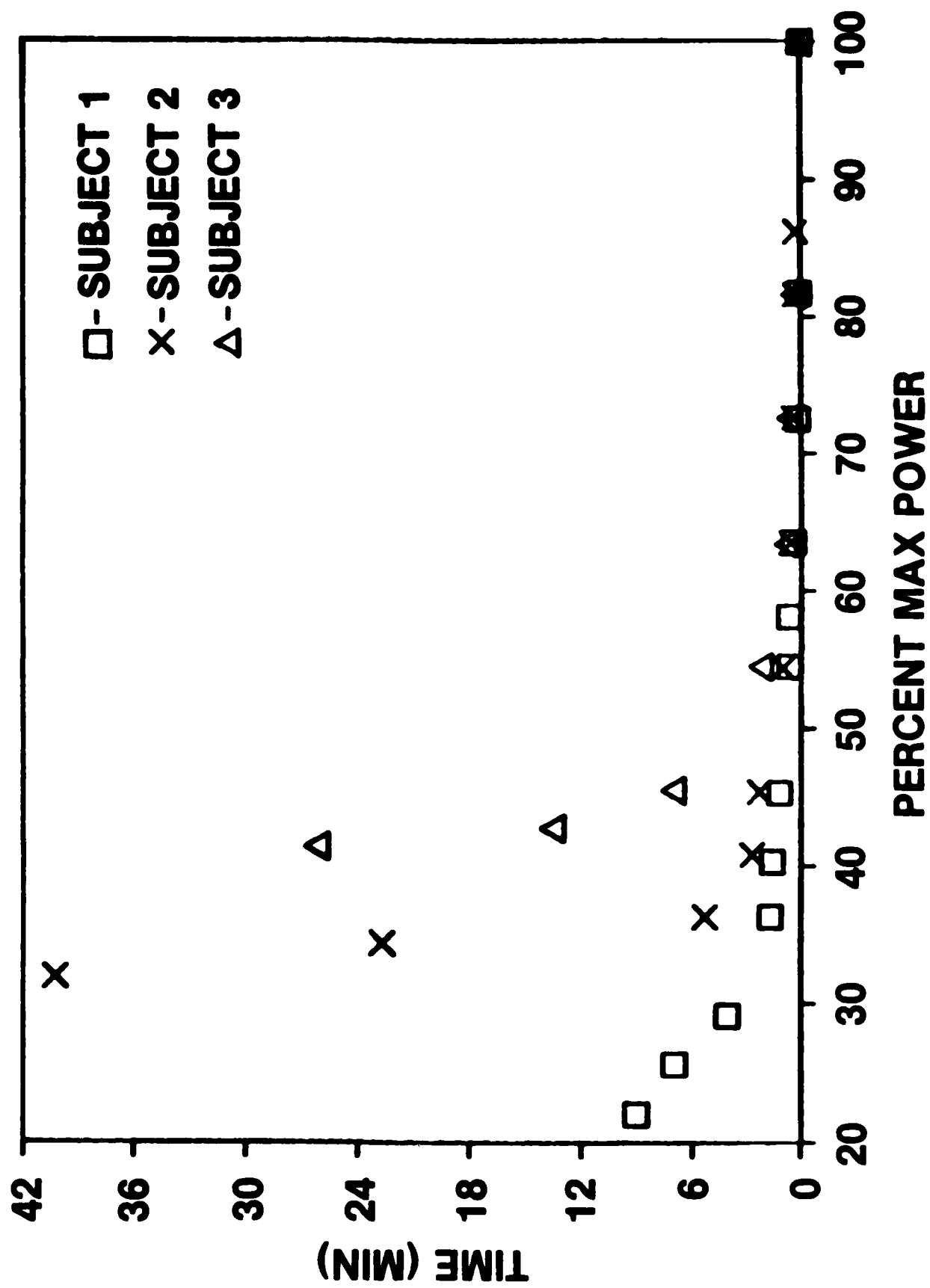
for: a) the fitting group, and b) three different individuals

Figure 3. Endurance time (min) vs. scaled power for the fitting group and
a plot of equation 4.









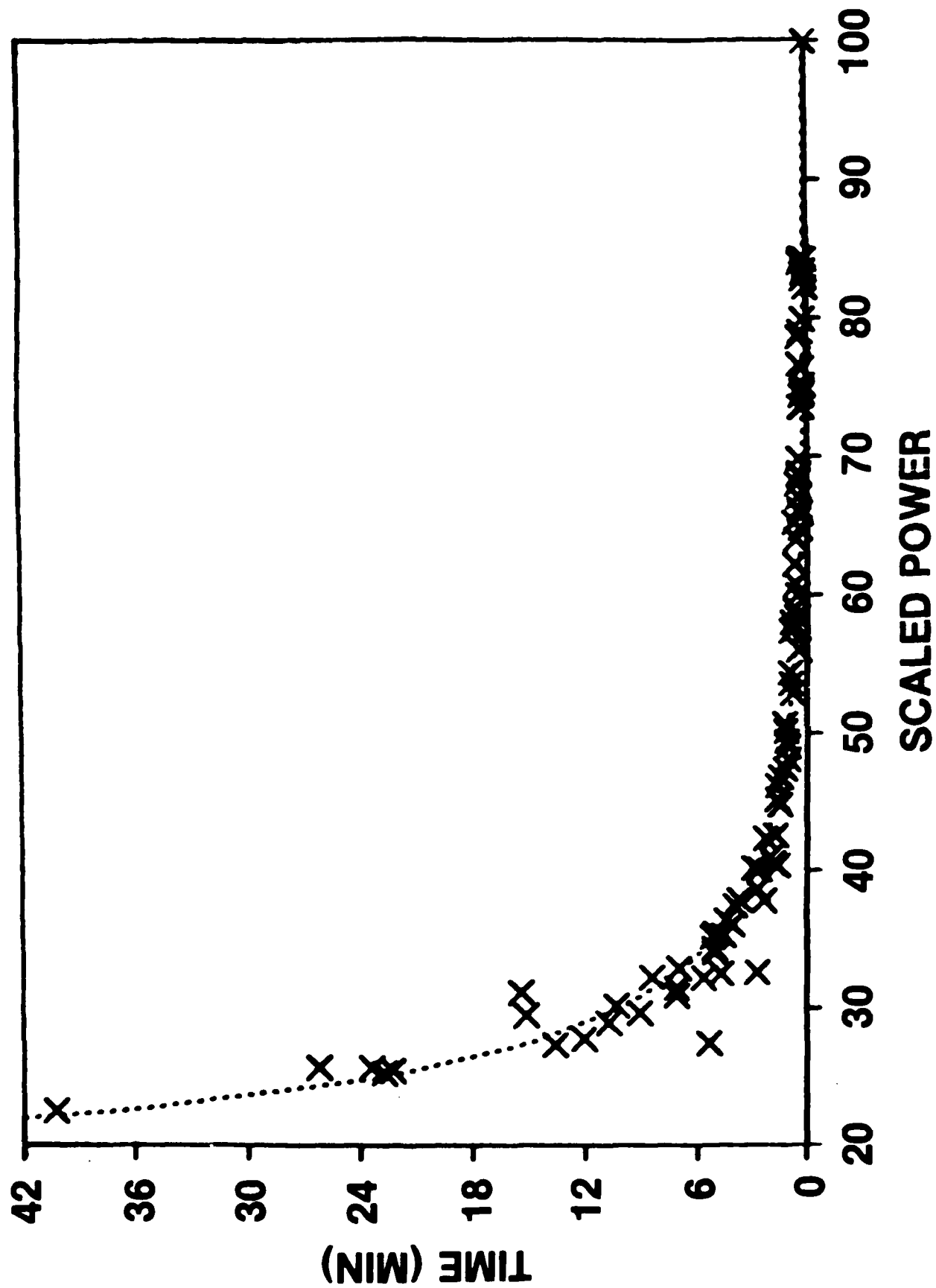


Table 1. Descriptive statistics for maximal power and the F scaling factor.

	<u>max power (W)</u>	<u>F</u>
mean	804	1.00
S.D.	137	.14
minimum	611	.81
maximum	1125	1.27

Table 2. Descriptive statistics on single test adequacy index.

<u>% max</u>	<u>mean</u>	<u>SD</u>
lowest *	1.00	.029
20-30	.99	.032
30-40	.99	.017
40-50	.99	.036
50-60	1.04	.063
60-70	1.12	.073
70-80	1.14	.318
80-90	1.21	.695

* the lowest % of maximum at which each
individual was tested

AUTHORS' STATEMENT

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